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# КВАЗИРАСПРЕДЕЛЕННЫЙ ВОЛОКОННО-ОПТИЧЕСКИЙ ДАТЧИК ДЛЯ ВЫСОКОВОЛЬТНЫХ ИЗМЕРЕНИЙ

*М. А. КСЕНОФОНТОВ*[1], *А. В. ПОЛЯКОВ*[2]

[1]*Институт прикладных физических проблем им. А. Н. Севченко БГУ, ул. Курчатова, 7, 220045, г. Минск, Беларусь*
[2]*Белорусский государственный университет, пр. Независимости, 4, 220030, г. Минск, Беларусь*

***Аннотация.*** Для контроля высоковольтного напряжения применяется рециркуляционный метод измерений. Квазираспределенный волоконно-оптический датчик выполнен в виде замкнутого оптоэлектронного контура, образованного перестраиваемым источником излучения, чувствительными элементами, разделенными спектральными отражательными элементами, лавинными фотодиодами и блоком регенерации. В качестве источника излучения использовался двухволновой перестраиваемый волоконный кольцевой лазер, который имел выходную мощность излучения 4,5 мВт, спектральный интервал между линиями генерации 200 ГГц и спектральную ширину 22,8 ГГц. Чувствительным элементом данного прибора является одномодовое оптическое волокно, намотанное на пьезокерамическую трубку. Принцип измерения основан на обратном поперечном пьезоэффекте, в результате которого приложенное электрическое напряжение вызывает изменение размеров пьезокерамической трубки и длины намотанного волоконного световода. С применением теории связанных мод проведено моделирование спектрально-энергетических параметров пяти соседних по спектру волоконных решеток Брэгга и установлены характеристики решеток, позволяющие использовать их в качестве спектрально-селективных элементов. Изменение частоты рециркуляции на разных длинах волн дало возможность осуществлять контроль электрического напряжения в разных точках с высокой точностью. Оценена разрешающая способность таких датчиков, равная 4,3 Гц/кВ

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**Авторы:**
***Михаил Александрович Ксенофонтов*** – доктор физико-математических наук, доцент; заведующий лабораторией физикохимии полимерных материалов и природных органических соединений.
***Александр Владимирович Поляков*** – доктор физико-математических наук, доцент; профессор кафедры физики и аэрокосмических технологий факультета радиофизики и компьютерных технологий.

**Authors:**
***Michael A. Ksenofontov***, doctor of science (physics and mathematics), docent; head of the laboratory of physical chemistry of polymer materials and natural organic compounds.
*lab_dozator@mail.ru*
***Alexandre V. Polyakov***, doctor of science (physics and mathematics), docent; professor at the department of physics and aerospace technologies, faculty of radiophysics and computer technologies.
*polyakov@bsu.by*

для радиуса пьезокерамической трубки 12 см. Установлено, что при многоточечных измерениях для PZT-5H достигается относительная погрешность 0,30–0,45 % в диапазоне напряжений 20–150 кВ. Система предназначена для автоматизированного измерения электрического напряжения на распределительных трансформаторных станциях и высоковольтных линиях электропередач.

***Ключевые слова:*** квазираспределенный волоконно-оптический датчик; пьезоэлектрический эффект; частота рециркуляции; спектральное мультиплексирование; высоковольтные измерения; погрешность.

# QUASI-DISTRIBUTED FIBRE-OPTIC SENSOR FOR HIGH-VOLTAGE MEASUREMENTS

***M. A. KSENOFONTOV***[a]***, A. V. POLYAKOV***[b]

[a]*A. N. Sevchenko Institute of Applied Physical Problems, Belarusian State University, 7 Kurchatava Street, Minsk 220045, Belarus*
[b]*Belarusian State University, 4 Niezaliezhnasci Avenue, Minsk 220030, Belarus*

*Corresponding author: A. V. Polyakov (polyakov@bsu.by)*

***Abstract.*** The recirculation measurement method is used to control high voltage. The quasi-distributed fibre-optic sensor was constructed as a closed optoelectronic circuit formed by a tunable radiation source, sensitive elements separated by spectral reflective elements, avalanche photodiodes and a regeneration block. A dual-wavelength tunable fibre ring laser was used as a radiation source had an output radiation power of 4.5 mW, two generated wavelengths separated by 200 GHz with a line width of 22.8 GHz. The sensitive element of this device was the single mode optical fibre, wound onto the piezoceramic tube. The measurement principle is based on the inverse transverse piezoelectric effect, as a result of which the applied electric voltage causes a change in the dimensions of the piezoceramic tube and the length of the wound optical fibre. Based on the theory of coupled modes, the spectral-energy parameters of five adjacent fibre Bragg gratings in the spectrum were simulated and the characteristics of the gratings were established, allowing them to be used as spectral-selective elements. Changing the recirculation frequency at different wavelengths allowed the electric voltage to be monitored at different points with high accuracy. The resolution of these sensors is estimated to be 4.3 Hz/kV for a piezoelectric ceramic tube radius of 12 cm. Relative accuracy of 0.30–0.45 % for the PZT-5H at the multi-point measurements is achieved in the voltage range of 20–150 kV. The system is designed for automated measurement of electrical voltage at distribution transformer stations and high-voltage power lines.

***Keywords:*** quasi-distributed fibre-optic sensor; piezoelectric effect; recirculation frequency; spectral multiplexing; high-voltage measurements; accuracy.

## Introduction

In the last three decades, with the development of optoelectronics and fibre optics, fibre-optic sensors (FOS) began to stand out among measuring devices due to such advantages as: fire, explosion, spark safety; resistance to chemical, mechanical, corrosive effects; insensitivity to electromagnetic interference; long length with low weight; provision of multiplexing of individual sensors into complex measuring systems; the possibility of easy interfacing with existing fibre-optic networks and, as a result, the possibility of transmitting information over long distances.

The problem of long-distance electric power transmission is associated with the use of high voltages, which requires solving complex technical problems related to reducing the cost of electric energy and ensuring high reliability of power supply. The difficulty of measuring high voltages is due to the fact that the accuracy of measurement is affected by factors that have intricate and random dependencies on electromagnetic interference, temperature and other external conditions. High-voltage monitoring is impossible without the use of special measuring equipment.

Most optical high-voltage sensors are based on the electro-optic Kerr effect and the Pockels effect [1–5]. Birefringence, which occurs in the Pockels cell under the influence of an electric field, is the physical basis for the operation of such optical voltage sensors. In this case, the optical fibre is used as a channel for transmitting information. In this scheme, the Pockels effect retains linearity only in a limited range. Electrostrictive [6] and piezoelectric materials [7–9], rigidly connected to the optical fibre, have been successfully used as a voltage conversion element. The linear piezoelectric effect for voltage is converted into a change in the length of the optical fiber and causes a change in the phase of the light wave propagating in the fibre, which is detected using interferometric methods [10]. The sensor consists of a section of single-mode optical fibre wound on a piezoelectric ceramic tube and a Mach – Zehnder interferometer [11] or Michelson interferometer [12]. It was shown [13] for the prototype after temperature and wavelength correction the accuracy reaches of 0.2 % for 110 kV.

The highest measurement accuracy is achieved by phase interference type FOSs, however, the results of their measurements are highly dependent on the influence of mechanical impacts, vibration, differential zero drift under the influence of temperature and pressure fluctuations, and polarisation control.

The design of the sensing element of the fibre-optic voltage sensors (FOVS), reported [14; 15], consists of an optical fibre Bragg grating, fixed along the diameter of the piezoelectric ceramic tube (PZT). The deformation caused on the PZT, when a voltage is applied, is transduced to the fibre grating as an axial strain, which results in a shift in the resonance frequency of the grating is affected by any strain applied along its length.

To obtain a linear measurement dependence without hysteresis, it is necessary to use an appropriate piezoelectric material, considering that the deformation of PZT depends on its shape, composition and polarisation process. Elimination of hysteresis in PZT materials is of primary importance for sensor applications. The PZT-4, manufactured by *Sparkle Ceramics* (United Kingdom), is known as hard type and is recommended for medium- and high-voltage applications. It has a low piezoelectric charge constant and a high resonance frequency, which guarantees that the set will not resonate close to the normal working frequency of 50 Hz [16]. For PZT-4, the sensitivity value of FOVS with fibre Bragg grating was 232 pm/kV [16]. Better sensitivities can be achieved by choosing a different PZT type with a higher piezoelectric charge constant, for instance, PZT-5A or PZT-5H. A prototype [17] was tested in the laboratory and showed a maximum linearity error of less than 3 % of full-scale range (FSR) for input voltages up to 14 kVrms with a signal-to-noise ratio of 55 dB, allowing measurements with a resolution of less than 0.2–0.5 % of FSR. The accuracy of FOVS measurements based on fibre Bragg grating is limited by the width of the reflection spectral line, as well as the resolution of the optical spectrum analyser.

To avoid the mentioned imperfections, in this paper we offered to measure voltage by fibre-optic recirculation sensor (FORS), with may be used for the telemetric monitoring of high-power distribution lines [18].

## Quasi-distributed high-voltage sensor

**Operation principles.** In given paper it is offered one of updating of FORS. This device represents quasi-distributed sensor. The optical fibre sensors with temporary representation of the information alongside with cheapness and high accuracy have also other advantages: allow to exclude or strongly reduce instability and drift of signals; there is no problem of an establishment and maintenance of a zero basic level; the data on a position and duration of pulses, and also frequency of the following once are transferred practically without easing of a signal; the ambiguity of received results inherent to interferometrical measuring converters is excluded; the function of transformation is linear in wide range [19].

Based on the generalisation of theoretical and experimental data, a new method for high-voltage measuring by fibre optic sensors has been developed. It is based on recording the recirculation frequency of single optical pulses with their restoration by amplitude, shape and duration at each recirculation cycle in a closed fibre-optic system. In this case, the optical fibre is both a sensitive element and a channel for transmitting information. While maintaining the simplicity and reliability of the design inherent in amplitude FOSs, in recirculation FOSs there is no need to measure minor changes in the amplitude of signals against the background of noise, which increases the resolution of such systems.

The schematic of the sensor is shown in fig. 1. The operating principle of the measuring system is as follows. A dual-wavelength tunable fibre ring laser (TFRL) generates radiation pulses at two wavelengths. Fibre Bragg gratings (FBG) with different periods, installed at the beginning and at the end of the sensing element, provide reflection of these pulses. The optical fibre (OF) with reflecting mirror (RM) at the end, together with the FBG, directional coupler (DC), photodiode (PD), threshold device (TD), commutator (COM), regeneration block (RB), tunable electronic delay-line (TEDL) and TFRL form a closed recirculation loop. Two recirculation frequencies corresponding to two wavelengths are recorded by a dual-channel frequency counter (FC) and the difference frequency in the microprocessor (CPU) is converted into a measured value. The microprocessor also performs general control of the measuring system. The sensing element is PZT with a tightly wound single-mode OF. At the beginning and end of the sensitive element, FBGs with different Bragg reflection wavelengths are located. The measurement principle is based on the inverse transverse piezoelectric effect. If an electric voltage is applied to the PZT, its transverse dimensions will change and, consequently, the OF length will change, which will lead to a change in the recirculation frequency. High-speed germanium or InGaAs avalanche photodiode (APD) can be used as a photodetector.

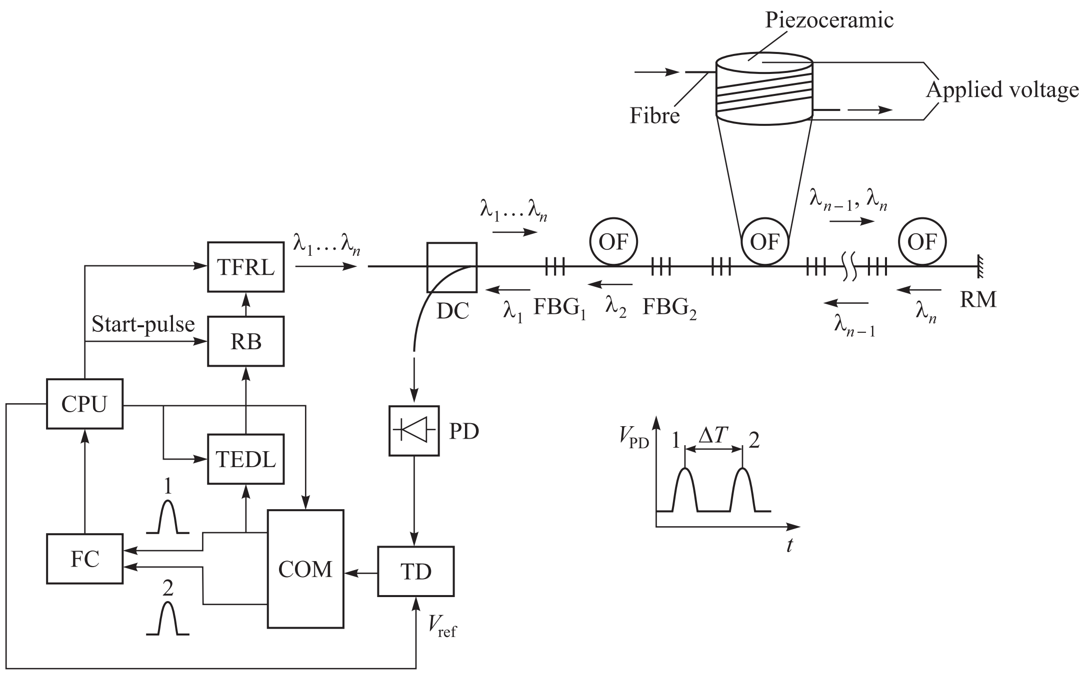


*Fig. 1.* Schematic of the quasi-distributed fibre-optic recirculating high-voltage sensor TFRL

For example, TFRL generates radiation pulses on wavelengths $\lambda_1$ and $\lambda_2$. The pulse in wavelength $\lambda_1$ is reflected from $FBG_1$ and the pulse in wavelength $\lambda_2$ is reflected from $FBG_2$ and its delay concerning the first pulse is determined by the double length of the first OF section. These pulses are detected by PD and get on the threshold device. The threshold device on the basis of comparator Am685 is necessary to exclude malfunction on noise pulses. The pulses from TD output are divided by the switchboard. The first pulse through a turning electronic delay-line and RB moves again on TFRL which generates new two pulses and thus recirculating process is formed. The two channels digital frequency counter measure recirculating frequency of the first pulse $f_1$ and second pulse $f_2$ at wavelengths $\lambda_1$ and $\lambda_2$ respectively. The microprocessor calculates a difference of these frequencies $\Delta f = f_1 - f_2$. The deviation $\delta f$ of the difference $\Delta f$ due to a change in the OF length under the influence of the applied voltage is the object of measurements. For measurement of a voltage in other spatial point for $\frac{i}{2}$ OF section CPU retunes TFRL generation wavelengths on $\lambda_{i-1}$ and $\lambda_i$. The length of each fibre-optical section wound on PZT is equal 100 m.

**Dual-wavelength tunable fibre ring laser.** A schematic of dual-wavelength TFRL like [20] is shown in fig. 2. Ring-1 is composed of an erbium-doped fibre amplifier (EDFA), semiconductor optical amplifier (SOA), a 50 : 50 optical coupler (OC), two polarisation controllers (PCs), a tunable optical bandpass filter (TOBPF), and an fibre Fabry – Perot filter (FFPF).

The driven current of SOA must be properly selected. If it is too low, the SOA cannot offer sufficient inhomogeneous gain. Then, gain competition would dominate the duel-wavelength laser and make it unstable. Otherwise, if the SOA supplies too much gain, high noise and undesirable nonlinear effects would further degrade the performance of the laser [20]. We used quantumwell heteroepitaxial structure SOA on the basis of InGaAsP – InP, radiating at wavelength 1530–1565 nm. The maximal signal-to-noise ratio was observed at a pump current 150 mA, thus the factor of amplification coefficient was equaled 17 dB at input signal power −15 dBm and the amplification coefficient decreased up to 8 dB at increase of input power up to −3 dBm.

The EDFA consists of two polarisation independent isolators, a section of erbium-doped fibre (EDF) with length 10 m, 980/1550 WDM coupler, 980 nm pump laser with pump power no more than 100 mW, laser diode current source (LDCS), and laser diode temperature controller (LDTC) [21]. The EDFA gain is 16 dB and maximum output power is 12 dBm, spectral gain band is 35 nm in the wavelength range 1530–1565 nm, noise factor is 3–4 dB.

The propagation period of the signals along the main ring was 325 ns. Two fibre resonators Ring-2 and Ring-3 with a different cavity length 6 and 0.85 m respectively were connected to this ring using X-shaped optical splitters with a division ratio of 10 : 90. The lengths of the resonators were selected in such a way as to prevent beats arising among many longitudinal modes of the main ring and to increase the signal-to-noise ratio.

As a result, when 10 % of the radiation power was diverted to these resonators, the recorded signal-to-noise ratio, according to [20], was more than 30 dB.

Basic element of the FFPF is a piece of a single-mode OF with the end surface having the form of lens on which the semitransmitting mirror covering with high reflection index is sprayed. At FFPF length 0.5 mm and reflection index 0.7 the FSR is 200 GHz and 3 dB bandwidth is 22.8 GHz.

As the tunable optical bandpass filter it is used fibre interference filter manufactured by *DiCon Corporation* (USA) with following parameters: a tuning range of 1525–1565 nm, 3 nm passband width, the wavelength resolution of 0.05 nm, typical introduced losses of 1.5 dB, a maximum level of return reflection of –50 dB. The bandwidth of the tunable filter is sufficient to cover the range selected by the Fabry – Perot resonant filter, containing two wavelengths. Thus, two wavelengths, separated by 200 GHz (1.6 nm), were generated in the fibre ring laser. By tuning the bandpass filter, the required pair of Fabry – Perot resonator modes was selected, which was then generated. The tuning was stepwise with a step of 3 nm within the spectral range of 40 nm. The input of radiation pulses from the TFRL into the fibre-optic loop was carried out through an optical directional coupler (ODC).

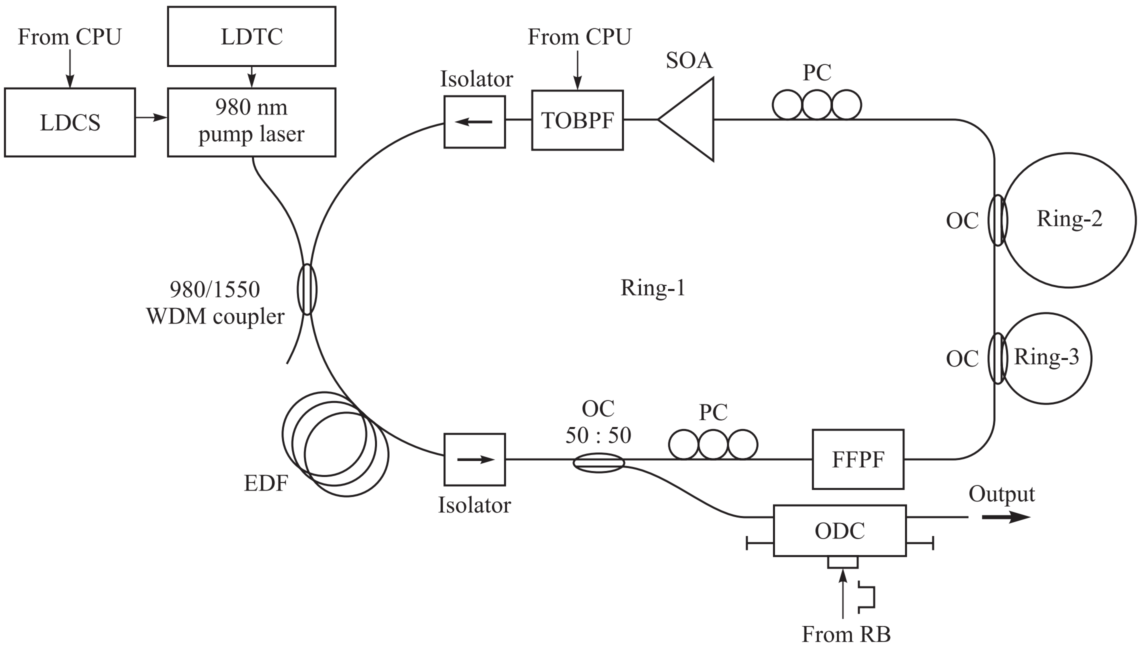


*Fig. 2.* Schematic diagram of the dual-wavelength TOBPF

Thus, two wavelengths were generated in the fibre ring laser, separated by 200 GHz (1.6 nm) with a generation line width of 22.8 GHz at a level of –3 dB. As a result, the laser radiation wavelength was tuned in the range of 40 nm within the wavelengths from 1525 to 1565 nm with a step of 3 nm, while the power fluctuations in the entire range did not exceed 0.9 dBm (fig. 3). The output radiation power of the ring fibre laser was 4.5 mW (6.5 dBm). The fibre laser was connected to the measuring section via a $LiNbO_3$ directional coupler with a switching loss of 3 dB.

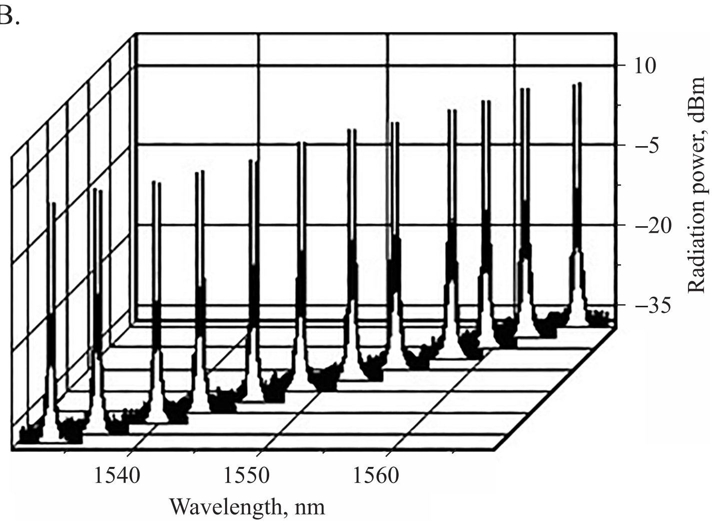


*Fig. 3*. Spectral tuning range of a ring fiber laser

**Fibre Bragg gratings.** In the developed quasi-distributed fibre-optic measuring systems, FBGs were used as spectrally selective elements. These gratings are sections formed in the fibre with a periodic change in the refractive index. The peculiarity of such gratings is that, depending on the period value, reflection occurs at one specific wavelength, while for other wavelengths the grating is transparent. The conditions for amplifying reflected light at a specific wavelength are called Bragg conditions, and the wavelength at which this occurs is called the Bragg wavelength:

$$\lambda_B = 2n_e\Lambda,$$

where $n_e$ is effective refraction index of a fibre core.

To find the field distribution in OF, the following assumptions were used: the optical fibre had no losses; the refractive index profile was stepwise and described by circ-functions whose centers coincided; the material was optically isotropic; the fibre was weakly guiding. With such assumptions, based on the coupled mode theory of D. K. W. Lam and B. K. Garside [22], the relative spectral reflectivity of the FBG with a constant amplitude and period of refractive index changes was described by the expression [23]

$$R(l, \lambda) = \frac{\Omega^2 \sinh^2(sl)}{\Delta k^2 \sinh^2(sl) + s^2 \cosh^2(sl)},$$

where $R(l, \lambda)$ is function dependent on grating length $l$ and radiation wavelength $\lambda$; $\Omega$ is connection factor; $k = \frac{2\pi n_e}{\lambda_B}$ is wave vector of a Bragg grating; $\Delta k = k - \frac{2\pi n_0}{\lambda}$ is detuning factor of a wave vector; $s^2 = \Omega^2 - \Delta k^2$. Connection factor $\Omega$ for Bragg structure with sinusoidal change of a refraction index is described by the equation

$$\Omega = \frac{\pi\Delta n}{\lambda}\left(1 - \frac{\lambda^2}{4\pi^2 d_c^2\left(n_0^2 - n_{cv}^2\right)}\right),$$

where $d_c$ is diameter of a fibre core; $n_0$ is average refraction index of a core; $n_{cv}$ is refraction index of an OF cover; $\Delta n$ is the modulation amplitude of the induced refraction index for FBG (is usual $\Delta n$ value makes $10^{-5}$–$10^{-3}$).

Profile of a refraction index of homogeneous Bragg grating can be submitted as

$$n(z) = n_0 + \Delta n \cos\frac{2\pi z}{\Lambda},$$

where $z$ is distance along an fibre axis.

Figure 4 shows the results of calculating the relative spectral reflectance of five adjacent spectra FBG with the following values: $l = 4$ mm; $\Delta n = 3 \cdot 10^{-4}$; $d_c = 9$ μm; $n_0 = 1.468$; $n_{cv} = 1.463\,8$; $n_e = 1.468\,2$; $\Lambda = 0.527\,6$–$0.529\,8$ μm. The values of the reflection spectrum width for the central grating at half-height $\Delta\lambda_{1/2} = 0.37$ nm (~50 GHz) were obtained, while the central lines of the Bragg reflection wavelengths were separated by 1.6 nm (200 GHz). The side lobe suppression level is –8 dB.

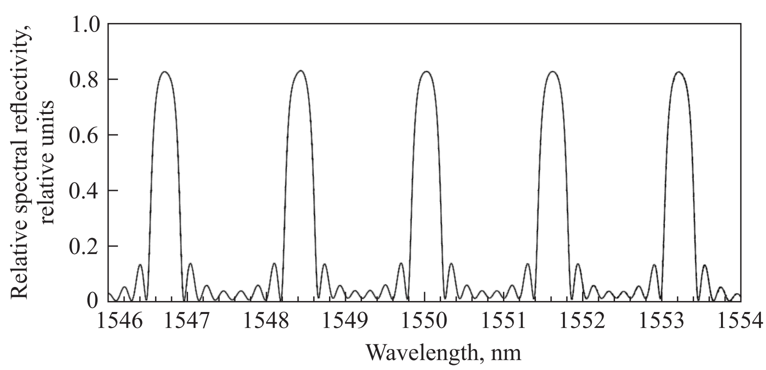


*Fig. 4.* The result of modelling the five FBGs relative spectral reflectance for a single-mode fibre at Δλ = 1.6 nm

The spectral parameters of Bragg gratings correspond to the parameters of a dual-wavelength tunable fibre ring laser and FBGs with these characteristics can serve as spectrally selective elements.

## Results of numerical simulation and discussion

Measurement accuracy of sensor is defined the stability of recirculation frequency. The size of relative long-term instability of recirculation frequency $\chi$ (RLTI) is one of the major factors defining metrological characteristics of fibre-optical recirculating sensors. The measurement error of FOS recirculation is defined by a condition that the additional increment (reduction) of circulating pulse delay time under the influence of voltage should exceed the maximum size of recirculation frequency instability $\chi_{max}$, caused by the independency of measured voltage external and internal destabilising factors [24]. Minimum value of the voltage change $\Delta U_{min}$, which can register the sensor, must exceed long-term instability of recirculating frequencies difference $\delta f_{min}$ of two pulses in closed optoelectronic contour:

$$\delta f_{min} \geq \sqrt{2}\chi_{max}\Delta f.$$

Based on the inverse piezoelectric effect reached under an applied voltage, a radial deformation is produced in the ceramic disc. The radial response of the piezoceramic under the influence of an applied voltage $U$ is given by $\frac{\Delta r}{r} = \frac{2\beta_{31}U}{h}$, where $r$ is the disc radius and $h$ is its thickness.

The expression for the resolution of the measurement method for the $i$ measuring section is

$$\Delta U_{min} = \frac{\sqrt{2}\chi_{max}\left(L_0 d_f + 2\pi\xi\gamma irh\right)}{4\pi\xi\gamma\left(1-\sqrt{2}\chi_{max}\right)\beta_{31} r}, \tag{1}$$

where $L_0$ is the length of the undeformed fibre ($L_0 = 20$ m); $\xi$ is the coefficient considering the photoelasticity effect in the stretched part of the fibre (for quartz fibres, $\xi = 0.78$); $\gamma$ is the coupling coefficient characterising the degree of transmission of the tube deformation to the fibre (when they are rigidly coupled, $\gamma \approx 0.8$–$0.9$); $r$ and $h$ are the radius and thickness of the tube respectively; $i$ is the number of the measuring tube; $d_f = 250$ μm is the fibre diameter [25].

For PZT-4D-type piezoceramics based on titanium and lead zirconate, the maximum electric field strength $E_v = 14.4$ kV/cm; therefore, to measure voltages, for example, up to 20–150 kV, the tube thickness $h$ must be at least 1.5–10.5 cm. The most common PZT-4D and PZT-5H piezoceramic have a constant $\beta_{31} = 1.35 \cdot 10^{-10}$ m/V and $2.74 \cdot 10^{-10}$ m/V respectively. This types of piezoceramic tube are selected due to its linear characteristic in a wide range of measured voltages and the absence of a hysteresis loop [25].

Resulting value of RLTI grows out of imposing of variety both connected among themselves, and not connected fundamental (caused by physical principles of optoelectronic elements functioning) and technical (instability of feeding voltage, environment temperatures, etc.) sources of fluctuations [24]. Experimental researches of RLTI dependence from operating modes of sensor elements have been carried out [26]. Results of researches are presented on fig. 5. The photodetector consisted from InGaAs-APD with spectral sensitivity 8.8–9.4 A/W for a frequency band 1 GHz (NEC NR4210 and EG & G Optoelectronics C30645E type) and photodiode loading resistance $R = 50$ Ω. Losses in a fibre was 0.2 dB/km (singlemode fibres of Corning SMF-28 9/125 and Fujikura SM type). As the counter it was used two 225 MHz channels Agilent 53132A/010 universal frequency counter with high-stability timebase. The analysis of dependences $\chi\left(U_{ref}\right)$ has shown, that in interval $U_{ref} = (0.3–0.8)U_{PD}$ the $\chi$ magnitude practically does not change as the threshold of operation corresponded to a linear site of the pulse front. Degradation of RLTI at the further increase in a reference it is caused by an increasing influence of fluctuations of circulation pulse amplitude on the operation moments of TD on a nonlinear site of a pulse front. Reduction of $U_{ref}$ magnitude led to effect of self-excitation of TD and recirculation breakup. Experimental values shown on fig. 5 started to be fixed through 15 min from the moment of start of circulation when the system was included into rather stable condition, at following parameters: $P = 4$ mW and $U_{ref} = 0.5U_{PD}$. At all measurements gate time is 1 s. According to fig. 5 at $L > 100$ m $\chi_{max} < 2 \cdot 10^{-6}$. Carried out researches have shown, that increase gate time upto 10 s and increase fibre length upto 500 m and more slightly reduce $\chi$ value. It states confirms that recirculation FOS possess property to accumulate fluctuation in the course of circulation. The relative long-term instability of the recirculation frequency was experimentally determined in the absence of applied voltage in order to establish the influence of destabilising factors unrelated to the measured physical quantity on the measurement accuracy of recirculation fibre-optic sensors.

Continuous monitoring of the following conditions according to fig. 5 is required:

$$\text{if } 2\left(L_0 + \frac{2\pi irh}{d_f}\right) < 100 \text{ m, then } \chi_{max} = 5 \cdot 10^{-6},$$

$$\text{if } 2\left(L_0 + \frac{2\pi irh}{d_f}\right) \geq 100 \text{ m, then } \chi_{max} = 2 \cdot 10^{-6}.$$

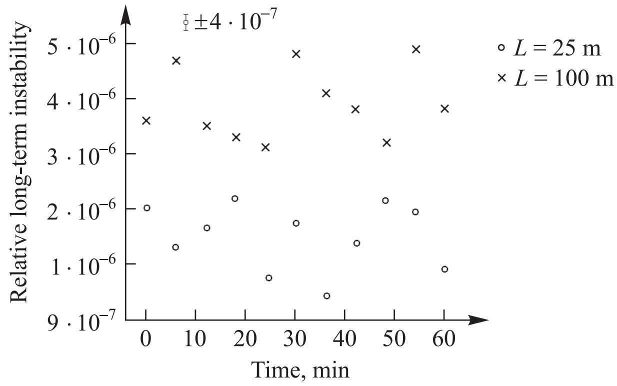


*Fig. 5.* Dynamics of relative long-term instability change of recirculating frequency

The change $\delta f$ of the difference $\Delta f$ due to a change in the length of the optical fibre under the influence of the applied voltage on the $i = 1$ sensitive element was found according to the formula

$$\delta f = \frac{c}{2}\left[\frac{1}{L_0 n_\mathrm{e} + n_\mathrm{e}\xi\gamma\dfrac{2\pi r h}{d_\mathrm{f}}} - \frac{1}{L_0 n_\mathrm{e} + n_\mathrm{e}\xi\gamma\dfrac{2\pi h\left(r + \Delta r\right)}{d_\mathrm{f}}}\right]. \tag{2}$$

Figure 6 shows the dependences of the change in the recirculation frequency on the measured electrical voltage at different PZTs radii ($r$) calculated according to equation (2). These dependences were approximated by a straight line of the form $\delta f = bU$, where $b$ is the sensitivity of the sensor. The sensitivity of the fibre-optic voltage sensor increased for piezoceramic tubes with radii up to 12–15 cm, a further increase in the radius of the tubes did not improve the metrological characteristics of the sensor, while its sensitivity reached 4.3 Hz/kV.

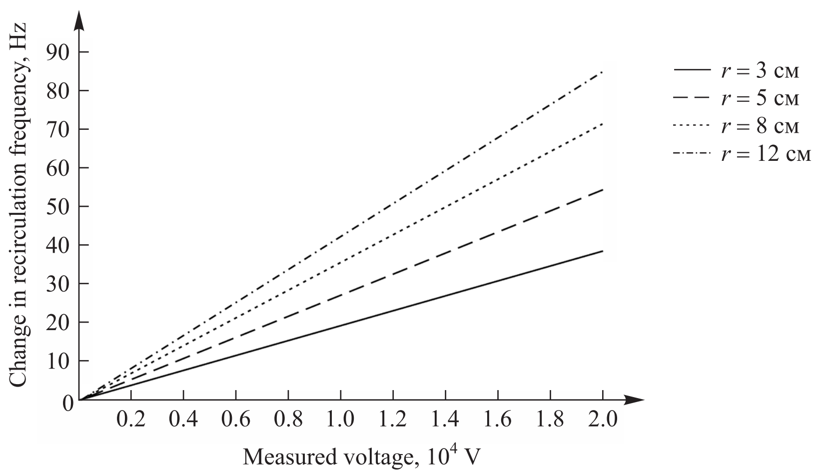


*Fig. 6.* Dependences of the change in recirculation frequency on the measured voltage

In practice, there are often cases when several high-voltage lines with different voltages have to be controlled simultaneously. Let us consider the monitoring variant at the distribution station, where there are lines of various voltages: $U_1 = 20$ kV, $U_2 = 35$ kV, $U_3 = 50$ kV, $U_4 = 110$ kV, and $U_5 = 150$ kV. In this case, equation (1) becomes

$$\Delta U_\mathrm{min} = \frac{\sqrt{2}\chi_\mathrm{max}\left(Ld_\mathrm{f} + 2\pi\xi\gamma r_i h_i\right)}{4\pi\xi\gamma\left(1 - \sqrt{2}\chi_\mathrm{max}\right)\beta_{31} r_i}, \tag{3}$$

where

$$L = L_0 + \sum_{j=0}^{i-1} 2\pi\left(r_j + 2\beta_{31} U_j \frac{r_j}{h_j}\right)\frac{h_j}{d_\mathrm{f}}. \tag{4}$$

Thus, the tubes should be of different thicknesses: $h_1 = 1.5$ cm, $h_2 = 2.4$ cm, $h_3 = 3.5$ cm, $h_4 = 7.6$ cm, and $h_5 = 10.4$ cm.

Since, according to equation (3), the error increases with an increase in the total beam waveguide length, to reduce the error, it is reasonable to use fibre beam waveguides of the same length equal to, for example, the length of the fibre for winding the tube of the smallest height for winding each piezoceramic tube. In this case, equation (4) becomes

$$L = L_0 + \sum_{j=0}^{i-1} 2\pi\left(r_j + 2\beta_{31}U_j \frac{r_j}{h_j}\right)\frac{h_1}{d_\mathrm{f}}. \quad (5)$$

To determine the measurement with minimum error, two PZT tubes of the measuring system were investigated. Electric networks with a voltage of 20–150 kV are the most widespread and mass high-voltage distribution lines intended for power supply inside cities, district settlements, large enterprises, the monitoring of which is of the greatest practical interest. The maximum voltage that can be measured by the developed fibre-optic sensor is limited by the condition that the relative elongation of the quartz fibre light guide should not exceed 0.36 %. This ensures a service life of more than 10 years. For the investigation voltage range, the relative longitudinal deformation of the fibre did not exceed 0.1 %. The results of calculations by equations (3), (5) for tubes made of ceramics PZT-4D and PZT-5H are presented in fig. 7 ($i = 1$, $U_1 = 20$ kV; $i = 2$, $U_2 = 35$ kV; $i = 3$, $U_3 = 50$ kV; $i = 4$, $U_4 = 110$ kV; $i = 5$, $U_5 = 150$ kV). With an increase in the controlled voltage, the relative accuracy of the sensors with PZT-5H tubes equalise substantially over the entire range of high voltages and are in the range of 0.30–0.45 %, which is preferable for practical use. In the case of PZT-4D, this range is 0.6–0.9 %.

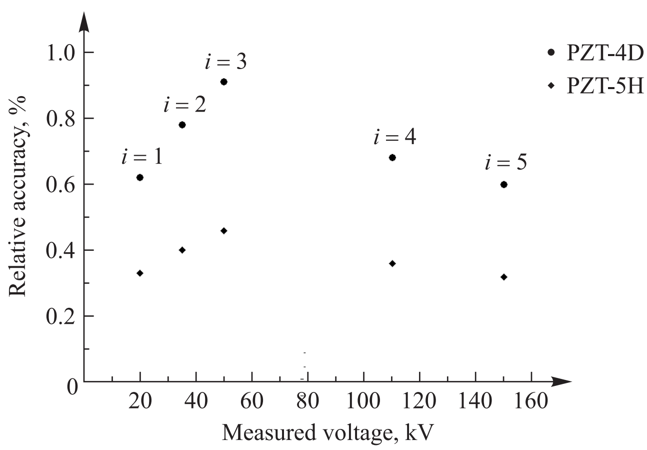


*Fig. 7.* Dependences of the sensor relative accuracy on the measured voltage for fibre sections of equal lengths for two different PZT tubes

## Conclusions

The design of the quasi-distributed piezoelectrically modulated fibre-optic high-voltage sensor has been investigated. The sensitive elements of this device were the OF sections, divided by spectral reflective elements. Radiation source is dual-wavelength tunable fibre ring laser, which is tunabled in a C-range $\lambda = 1535–1565$ nm, has output power $P = 4.5 \cdot 10^{-3}$ W and two wavelengths were generated simultaneously, separated by 200 GHz (1.6 nm) with a generation line width of 22.8 GHz at a level of −3 dB. Spectral reflective elements are FBGs with different grating period. The measurement principle is based on recirculating frequency registration of a single pulse with its periodic 2R-regeneration on different wavelengths. Piezoelectric ceramic PZT-4D and PZT-5H types were found to be appropriate for this application. Sensor sensitivity reached 4.3 Hz/kV for the PZT radius $r = 12$ cm. This frequency-output sensor has the relative accuracy not exceeding 0.30–0.45 % for PZT-5H at the multi-point measurements in the voltage range of 20–150 kV.

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